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Noise reduction panel arrangement and method of calibrating such a panel arrangement

The present invention relates to a noise reduction arrangement comprising:

- a plurality of actuators for generating secondary noise to reduce primary noise generated by at least one primary source, the plurality of actuators being located in a first surface;
- a plurality of sensors for sensing a total amount of noise resulting from the primary noise after being reduced by the secondary noise and for generating a plurality of sensor signals, the plurality of sensors being located in a second surface arranged substantially parallel to the first surface;
- a plurality of control means for controlling the actuators based on the sensor signals.

Such an arrangement is known from S.J. Elliott et al., Interaction Between Multiple Feedforward Active Control Systems, IEEE Transactions on Speech and Audio Processing, Vol. 2, No. 4, 1994, pp. 521-530 [1]. In this article Elliott et al. describe a noise reduction system having a panel of actuators arranged in a first plane and a plurality of error sensors in a second plane. The first and second planes are parallel to one another. Elliott et al. present a mathematical model of a decentralized adaptive feedforward control system. They also present results of some physical examples in which there are two actuators and two error sensors. In these examples, Elliott et al. introduce the mutual distances between the error sensors and the actuators as important parameters to derive conditions as to when such a system is stable. In the physical examples given, the distance between the two planes is about 0.3 times the distance between the two actuators. Elliott et al. do not disclose the presence of an optimum distance between the two planes as a function of the mutual distance between actuators.

X. Qui, e.a., A Comparison of Near-field Acoustic Error Sensing Strategies for the Active Control of Harmonic Free Field Sound Radiation, Journal of Sound and Vibration, 1998, 215(1), pp. 81-103 [2], disclose the results of a

study to find the best location of an error sensor relative to a primary noise source. However, this study is limited to a harmonic sound field radiated by a monopole primary source and by a dipole-like pair of primary sources. In both cases the actuator is a monopole radiating at the same frequency as the primary source. No plurality of actuators and plurality of error sensors arranged in respective planes are disclosed.

An active high transmission loss panel is disclosed in WO-A-94/05005. However, in this patent document the actuators and sensors are all located in the same plane.

The present invention is directed to a noise reduction arrangement having a plurality of actuators in a first surface and a plurality of error sensors in a second surface in which the reduction of noise is optimized as a function of the distance between the surfaces. The surfaces may be planes, like in the arrangement of Elliott et al. [1], but they may also deviate from planes. They may, e.g., be slightly curved.

Thus, the noise reduction arrangement as defined above is characterized in that the distance between the first and second surfaces is such that reduction in power RP of the total amount of noise relative to the primary noise within a predetermined frequency band is within the following range:

$$0.9 \times RP_{max} \leq RP \leq RP_{max}$$

in which RP_{max} is maximum obtainable reduction in power of the total amount of noise relative to the primary noise, where both RP and RP_{max} are expressed in decibel.

The present invention is based on the insight that a maximum reduction shows up in the curve representing the reduction of the total amount of sound power relative to the primary noise as a function of the distance between the surfaces. The actual optimum distance where the maximum occurs depends on several parameters, like the number of actuators, the number of sensors, the ratio between these two numbers, the actual arrangement of the actuators and the actual arrangement of the sensors. The optimum distance can be established by testing while increasing the distance between the surfaces from 0, while adjusting a predetermined control parameter (ß) to maintain stability.

In one of the arrangements, the number of sensors equals the number of

actuators and equals the number of controllers, each controller receiving one of the plurality of sensor signals as input signal and controlling one of the plurality of the actuators. When, in such an arrangement, the plurality of actuators are arranged in rows and columns, mutual distances between adjacent columns and mutual distances between adjacent rows are equal to a predetermined actuator distance d_x and the plurality of sensors are arranged in the same way as the plurality of actuators, the distance d between the first and the second surfaces preferably meets the following condition:

$$0.5xd_x \leq d \leq d_x.$$

In an alternative arrangement, the number of sensors does not equal the number of actuators. When in such an arrangement the plurality of actuators are arranged in rows and columns, mutual distances between adjacent columns and mutual distances between adjacent rows are equal to a predetermined actuator distance d_x, the plurality of sensors are arranged in a regular pattern of rows and columns and each actuator is controlled based on a number of sensor signals, the distance d between the first and the second surfaces preferably meets the following condition:

$$0.5xd_x \leq d \leq d_x.$$

In one embodiment, the arrangement includes a supervising controller for monitoring long-term behaviour of the arrangement and for modifying control parameters of the controllers in order to ensure overall stability of the arrangement.

The present invention also relates to a method of calibrating a noise reduction arrangement comprising:

- providing a plurality of actuators for generating secondary noise to reduce primary noise generated by at least one primary source, the plurality of actuators being located in a first surface;
- providing a plurality of sensors for sensing a total amount of noise resulting from the primary noise as reduced by the secondary noise and for generating a plurality of sensor signals, the plurality of sensors being located in a second surface arranged substantially parallel to the first surface;
- providing a plurality of control means for controlling the actuators based

on the sensor signals,

characterized by the following steps:

- measuring reduction in power RP of the total amount of noise relative to the primary noise within a predetermined frequency band as a function of the distance between the first and second surfaces in a range of distances where the arrangement remains stable;
- determining a maximum obtainable reduction in power RP_{max} of the total amount of noise relative to the primary noise within said range;
- locating said sensors relative to said actuators such that the reduction in power RP of the total amount of noise relative to the primary noise within said predetermined frequency band is within the following range:

$$0.9xRP_{max} \le RP \le RP_{max}$$

where both RP and RP_{max} are expressed in decibel.

Hereinafter, the invention will be explained with reference to some drawings. The drawings and explanation are only given by way of example and are not intended to limit the scope of the present invention.

Figure 1a shows a front view of a plate provided with 48 actuators and 221 sensors in front of the plate;

Figure 1b shows a schematic cross section view of the arrangement according to figure 1a along line IB-IB in figure 1a;

Figure 1c shows a schematic electronic black box circuitry for controlling the actuators based on the sensor signals generated by the sensors;

Figure 2 shows sound power curves radiated from a plate without control, with global control and local control, respectively;

Figure 3 shows condition numbers for the curves shown in figure 2;

Figure 4 shows sound power curves as a function of frequency for an arrangement with 48 actuators and 48 sensors, the distance d between the actuator plane and the sensor plane being a parameter;

Figure 5 shows curves of broadband reduction in sound power for the arrangement of figure 4 taking into account all frequencies $f < c/2d_x$, with c the speed of sound in air and d_x the distance between adjacent actuators;

Figure 6 shows sound power curves as a function of frequency for an arrangement with 48 actuators and 221 sensors, the distance d between the

actuator plane and the sensor plane being a parameter;

Figure 7 shows curves of broadband reduction in sound power for the arrangement of figure 6, taking into account all frequencies $f < c/2d_x$;

Figure 8 shows sound power curves as a function of frequency for a global control arrangement with 48 actuators and 221 sensors, the distance d between the actuator plane and the sensor plane being a parameter;

Figure 9 shows broad band reduction of sound power according to figure 8, taking into account all frequencies $f < c/2d_x$;

Figure 10 shows sound power curves as a function of frequency for an arrangement in which the sound produced is reflected by a further plate parallel to the plate supporting the actuators, the reflection coefficient R being a parameter;

Figure 11 shows condition numbers for some of the curves shown in figure 8.

The description hereinafter presents simulation results of multiple local control systems intended for the active minimization of sound transmitted through a plate. The systems are analyzed for harmonic disturbances with respect to stability, convergence, reduction of transmitted sound power, the distance between actuators and sensors, and sensitivity for reverberating environments.

Figure 1a shows a baffled plate 1, which supports a plurality of actuators 3(n), n = 1, ..., N. In figure 1a 48 actuators 3(n) are shown. However, if required any other number of actuators 3(n) may be applied.

Supported by suitable supporting means (not shown), a plurality of sensors 2(m), m = 1, ..., M, is arranged in front of the plate 1. In figure 1a, 221 sensors 2(m) are shown. This means that any actuator 3(n) is associated with 9 sensors 2(m), adjacent actuators 3(n) sharing three of the sensors 2(m). Of course, any other number than 221 sensors 2(m) may be applied.

In figure 1a, the actuators 3(n) and the sensors 2(m) are regularly arranged in columns and rows at equal distances. However, this is not necessary.

Figure 1b shows a cross section through the arrangement according to figure 1a along line IB-IB. The same reference numbers refer to the same elements.

The acoustic radiation of primary noise source 4 causes a pressure field

p_{inc} incident on plate 1.

The mutual distance between two adjacent actuators is d_x. The mutual distance between two adjacent sensors 2(m) is d_{sens}. The distance between the actuator plane and the sensor plane is d.

Also shown is a reflective wall 8 which might be present in some embodiments, as will be explained below.

The actuators 3(n) are shown to be loudspeakers producing secondary noise $\mathbb{p}_s$ in order to reduce the primary noise $\mathbb{p}_p$. The total amount of resulting noise is measured by the sensors 2(m) which, preferably, are microphones or other pressure-sensitive devices.

Figure 1c shows a schematic electric diagram of the arrangement used in the invention. The same reference numbers refer to the same components as in figures 1a and 1b.

The sensors 2(m) produce sensor signals p(m) which are transferred to one or more controllers 5b(i), i = 1, 2, ..., I, e.g., in the way shown in figure 1c.

Figure 1c shows four controllers 5b(i), but there may be any other desired number. They provide one or more output signals $\mathbb{W}_i\mathbb{p}$ which are transmitted to controllers 5a(i) of a further set of controllers which directly control the actuators 3(n). The outputs $\mathbb{W}_i\mathbf{p}$ of the controllers 5b(i) are also input to a supervising controller 6.

In some embodiments use of one or more detection sensors 7(r), r = 1, ..., R, may be preferred. These detection sensors provide time-advanced information of the primary noise $\mathbb{p}_p$ to a distribution network 10. The distribution network 10 produces detection signals $v_{det}(i)$ for the controllers 5a(i). Both the distribution network 10 and the controllers 5a(i) and 5b(i) may be controlled by the supervising controller 6.

Each of the controllers 5a(i) controls one or more of the actuators 3(n) by means of control signals $\mathbb{u}_i$.

The supervising controller 6 may be used for monitoring long-term behaviour of the system and for modifying control parameters of the distribution network 10 and the controllers 5a(i), 5b(i) in order to ensure overall stability of the system.

It is noted that distribution network 10, controllers 5a(i), 5b(i), and super-

vising controller 6 are shown to be separate units, however, in reality they may be implemented by a single control unit performing all required functions.

Although figure 1c shows a situation in which each controller 5a(i) controls one actuator 3(n), in the theoretical analysis given below, it will be assumed that each controller 5a(i) controls K actuators 3(n).

Analysis

It is assumed that each of the controllers 5a(i), 5b(i) tries to minimize a cost function based on sensor signals local to that controller. The scalar cost functions J_i for the I controllers 5a(i) are written as

$$J_i = (W_i p)^H \, (W_i p) + u_i^H \beta_i u_i, \quad i = 1,\dots,I, \tag{1}$$

in which $\mathbf{p}$ is an M x 1 vector of sensor signals, $\mathbf{W}_i$ is a weighting matrix of dimensions P x M which provides a selection and weighting of P out of a total of M sensor signals used as error inputs for controller 5a(i); $\mathbf{u}_i$ is a K x 1-dimensional control signal for node i and β_i is a K x K dimensional effort weighting matrix. The sensor signals $\mathbf{p}$ result from the superposition of primary field contributions $\mathbf{p}_p$ and the contributions $\mathbf{p}_s$ due to N actuators. The latter contributions are given by $\mathbf{Gu}$, where $\mathbf{u}$ is an N x 1 vector denoting the control signals that drive the actuators and $\mathbf{G}$ is an M x N matrix of transfer functions between control signals and sensor signals. Hence,

$$p = p_p + Gu \tag{2}$$

Each controller 5a(i) drives K actuators, so N = IK.

Introducing the M x N matrix

$$\hat{G} = [F_1 G_1, F_2 G_2, \dots, F_I G_I] \tag{3}$$

with $\mathbf{F}_i = \mathbf{W}_i^H \mathbf{W}_i$

and $\mathbf{G}_i$ denoting the columns of $\mathbf{G}$ corresponding to controllers 5a(i) having dimensions M x K

and the N x N block-diagonal matrix β defined by

$$\beta = \begin{bmatrix} \beta_1 & 0 & \dots & 0 \\ 0 & \beta_2 & \dots & 0 \\ \dots & & & \dots \\ 0 & 0 & \dots & \beta_I \end{bmatrix} \qquad (4)$$

a linear system of N equations in u can be formulated:

$$(\hat{G}^H G + \beta)u = -\hat{G}^H p_p \qquad (5)$$

The present result explicitly includes the weighting factors for the error sensors. To arrive at the solution for u an iterative procedure is implemented in the system, such as the procedure described by Elliott et al. [5]. For interpretation of system behaviour the reader is referred to [1].

Simulations

In this section simulation results are given for an active control system intended to reduce the noise transmitted through plate 1. The sensors 2(m) are pressure sensors placed in the near-field of the plate 1. In the example, the actuators 3(n) are loudspeakers which are assumed to operate as constant volume velocity (monopole-like) sources. The plate 1 is assumed to be a 1 mm thick aluminium plate of 60 cm x 80 cm, having a modulus 7 x 10^{10} Pa, Poisson ratio of 0.3, hysteretic damping $\eta = 0.02$, and a density of 2.6 x 10^3 kg m^{-3}. The plate 1 is assumed to be simply supported and the incident field p_{inc} is a plane wave arriving at a direction α of 60 degrees to the plate normal. The basic configuration consists of 6 x 8 = 48 actuators and 13 x 17 = 221 sensors, as shown in Fig. 1a.

As opposed to active global control systems which minimize a global quadratic error criterion, stability is not guaranteed in multiple local systems. Assuming an iterative procedure to solve Eq. [5], the system is stable if the real parts of the eigenvalues λ_n, n = 1, ..., N of the matrix $\hat{G}^H G + \beta$ are positive [1]. The effort weighting matrix is taken to be the diagonal matrix $\beta = \beta I$. If the system is unstable for $\beta = 0$ the value of β will be set equal to - $\min_n \mathrm{Re}\lambda_n$, which makes the system just stable. Increasing the value of β further would enhance the stability margin and improve the speed of convergence of the iterative procedure, but also increase the residual radiated power. The convergence of some iterative procedures is governed by the ratio of the largest singular value

κ_1 to the smallest singular value κ_N [5], i.e. the condition number of the Hessian matrix $\hat{\mathbf{G}}^H\mathbf{G} + \mathbf{ß}$ [6].

Simulation methods

The models describing the vibration of the plate 1 can be found in [7]. The pressure $\mathbf{p}_p$ and $\mathbf{p}_s$ were computed with a weak form of a Fourier-type extrapolation technique in which singularities were evaluated by analytical integration [8]. In principle, the Boundary Element method as described in [9] can also be used but the latter method is less efficient for geometries of this and larger size. Formulas for zero extrapolation distance which were used can be found in [10].

Simulation results

The sound power without control and with control for various configurations are shown in Fig. 2. It was found that reductions could be obtained for frequencies for which both the mutual distance d_{sens} between the sensors and the mutual distance d_x between the actuators were smaller than approximately half of a wavelength. Moreover, the distance d between the sensors 2(m) and the plate 1 turns out to be an important parameter. Larger reductions are obtained if the pressure sensors 2(m) are moved away from the plate 1. This distance d can not be made arbitrarily large because of stability issues. The point of instability is reached at approximately a quarter of a wavelength from the plate if the ratio d/d_x is larger than a certain minimum value. If this ratio is smaller than this value, then the system is stable for all frequencies.

A large distance d might be detrimental for primary signals with short correlation lengths. For that purpose it may be useful to add one or more detection sensors 7(r) in the near-field of the plate.

The corresponding condition numbers are shown in Fig. 3. If a positive value of ß was used to make the system stable then the condition number is not shown.

Influence of d on the reduction

From the previous results it was found that the distance d between actuator plane and the sensor plane has a considerable influence on the achievable reduction of radiated sound power. It was also found that the distance d determines the frequency above which the system has to be stabilized by increas-

ing the value of ß. A higher value of ß leads to smaller reductions. The distance for instability is reached at approximately a quarter of a wavelength.

Clearly, two contradicting requirements for d have to be satisfied for broadband reductions. This is illustrated in Fig. 4, which shows sound power radiated from plate 1 without control and with local control using a 48 x 48, 1 x 1 system, i.e., using a total of 48 sensors and 48 actuators, 1 sensor and 1 actuator for each independent controller, with the distance d between the actuator plane and the sensor plane as parameter. If, at any frequency, the system is unstable a positive value for ß is used which makes the system just stable. If the system is stable ß = 0 is used. It can be seen that, for small d, reductions are increased by increasing d, particularly at low frequencies. However, the system has to be stabilized above the frequency where d equals a quarter of a wavelength. This stabilization leads to smaller reductions at high frequencies.

Hence, for broadband applications there might be an optimum value for d if the objective is to minimize the total acoustic power within a wide frequency range. It is assumed that all frequencies are taken into account for which half of the wavelength is larger than the actuator spacing d_x. For the present configuration, this corresponds to all frequencies smaller than $f < c/2.d_x = 1715$ Hz. The latter frequency is indicated by a dashed line in Fig. 4. This choice is somewhat arbitrary but not critical. It does correspond to the frequency range for which an active control system using a global error criterion leads to significant reductions of radiated sound power. For the present 1 x 1 system, the sensor spacing is identical to the actuator spacing. The broadband reductions for various values of d normalized to actuator spacing d_x are shown in figure 5. Indeed, it can be seen that there is a maximum in the reduction of broadband radiated sound power, both for constant weighting and for A-weighting. The maximum reduction is obtained for $d_x/2 \leq d \leq d_x$.

Additional factors might influence the optimum for d. In the case of stochastic disturbances and no reference sensor 7 in a feedforward link, the delay between the actuator and the sensor should be small compared to a characteristic correlation length of the disturbance signal. In addition, for smaller d, the condition number κ_1/κ_N of the system is lower, and often, therefore, the convergence of adaptive schemes better. These two considerations can lead to an optimum for

d which is somewhat smaller than given by figure 5. Then, for most systems occurring in practice, the optimum for d is in the range $0.1d_x < d < d_x$.

The results for a 221 x 48, 9 x 1 system, having half the distance between the sensors, are shown in Figs. 6 and 7. Figure 6 shows the sound power radiated from a plate in such a system, whereas figure 7 shows the broad-band reduction, again for all frequencies $f < c/2.d_x$. It can be seen that the maximum reduction which can be obtained is similar. The optimum value for d, as obtained from figure 7, is also within the range $d_x/2 \leq d \leq d_x$, although the peak in the reduction is wider than in figure 5. In practice therefore, the value of d for the 9 x 1 system will often be chosen somewhat smaller than for the 1 x 1 system.

The results for a global control system are shown in figures 8 and 9. The differences with the preceding local control systems are mainly in the high-frequency range. This leads to larger optimum values for d as well as less pronounced maxima.

Performance in reverberating environment

The performance of the local control system was also investigated for the case including reflecting parallel plane 8. The distance of this plane 8 to the actuators was taken to be 1 m. The reduction which can be obtained with this configuration is shown in figure 10 and the corresponding condition numbers in figure 11. It can be seen that for reflection coefficients smaller than or equal to 0.9 the control system remains stable and leads to reasonable reductions. For a reflection coefficient of 0.99 the possible reduction above approximately 500 Hz becomes less than for lower reflection coefficients.

List of symbols

$\mathbf{G}$	=	M x N matrix of transfer functions between control signals $\mathbf{u}$ and sensor signals $\mathbf{p}$
$\mathbf{G}_i$	=	M x K matrix of transfer functions between control signals $\mathbf{u}_i$ and sensor signals $\mathbf{p}$.
J_i	=	scalar cost function of controller 5(i); $i = 1, 2, ..., I$
$\mathbf{p}_p$	=	primary field contributions
$\mathbf{p}$	=	M x 1 vector denoting the sensor signals p(1), p(2), ..., p(m), ..., p(M)
$\mathbf{u}$	=	N x 1 vector denoting the control signals u(1), u(2), ..., u(n), ..., u(N), that drive the actuators 3(n)
$\mathbf{u}_i$	=	K x 1 vector denoting the control signals $u_i(1)$, $u_i(2)$, ..., $u_i(k)$, ..., $u_i(K)$ for node i
$\mathbf{W}_i$	=	weighting matrix of dimensions P x M
$\boldsymbol{\beta}_i$	=	K x K dimensional effort weighting matrix
κ_N	=	smallest singular value of Hessian matrix $\hat{\mathbf{G}}^H\mathbf{G} + \boldsymbol{\beta}$
κ_1	=	largest singular value of Hessian matrix $\hat{\mathbf{G}}^H\mathbf{G} + \boldsymbol{\beta}$

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Claims

1. Noise reduction arrangement comprising:

- a plurality of actuators (3(n)) for generating secondary noise (p_s) to reduce primary noise (p_p) generated by at least one primary source (4), the plurality of actuators (3(n)) being located in a first surface;
- a plurality of sensors (2(m)) for sensing a total amount of noise resulting from the primary noise after being reduced by the secondary noise and for generating a plurality of sensor signals (p(m)), the plurality of sensors (2(m)) being located in a second surface arranged substantially parallel to the first surface;
- a plurality of control means (5a(i), 5b(i)) for controlling the actuators (3(n)) based on the sensor signals (p(m)),

characterized in that the distance (d) between the first and second surfaces is such that reduction in power RP of the total amount of noise relative to the primary noise within a predetermined frequency band is within the following range:

$$0.9 \text{x} RP_{max} \leq RP \leq RP_{max}$$

in which RP_{max} is maximum obtainable reduction in power of the total amount of noise relative to the primary noise, where both RP and RP_{max} are expressed in decibel.

2. Arrangement according to claim 1 wherein the number of sensors (2(m)) equals the number of actuators (3(n)) and equals the number of controllers (5a(i), 5b(i)), each controller (5a(i), 5b(i)) receiving one of the plurality of sensor signals (p(m)) as input signal and controlling one of the plurality of the actuators (3(n)).

3. Arrangement according to claim 2 wherein the plurality of actuators are arranged in rows and columns, mutual distances between adjacent columns and mutual distances between adjacent rows being equal to a predetermined actuator distance d_x, the plurality of sensors being arranged in the same way as the plurality of actuators, the distance d between the first and the second surfaces meeting the following condition:

$$0.5xd_x \leq d \leq d_x$$

4. Arrangement according to claim 1 wherein the number of sensors does not equal the number of actuators.

5. Arrangement according to claim 1 or 4 wherein the actuators are divided into a plurality of subsets of actuators, each subset comprising one or more actuators and being controlled by a distinct controller (3(n)).

6. Arrangement according to claim 4 or 5 wherein the plurality of actuators are arranged in rows and columns, mutual distances between adjacent columns and mutual distances between adjacent rows being equal to a predetermined actuator distance d_x, the plurality of sensors being arranged in a regular pattern of rows and columns, each actuator being controlled based on a number of sensor signals, the distance d between the first and the second surfaces meeting the following condition:

$$0.5xd_x \leq d \leq d_x$$

7. Arrangement according to any of the preceding claims wherein a sound reflective wall (8) is present such that the second surface is between the first surface and the wall (8).

8. Arrangement according to any of the preceding claims wherein one or more detection sensors (7(r)) are arranged for providing one or more detection sensor signals ($v_{det}(i)$).

9. Arrangement according to any of the preceding claims wherein a supervising controller (6) is arranged for monitoring long-term behaviour of the arrangement and for modifying control parameters of the controllers (5a(i), 5b(i)) in order to ensure overall stability of the arrangement based on a predetermined error criterium as to the sensor signals (p(m)).

10. Method of calibrating a noise reduction arrangement comprising:

- providing a plurality of actuators (3(n)) for generating secondary noise (p_s) to reduce primary noise (p_p) generated by at least one primary source (4), the plurality of actuators (3(n)) being located in a first surface;
- providing a plurality of sensors (2(m)) for sensing a total amount of noise resulting from the primary noise as reduced by the secondary noise and for generating a plurality of sensor signals (p(m)), the plurality of sensors (2(m)) being located in a second surface arranged substantially parallel to the first surface;
- providing a plurality of control means (5a(i), 5b(i)) for controlling the actuators (3(n)) based on the sensor signals (p(m)),

characterized by the following steps:

- measuring reduction in power RP of the total amount of noise relative to the primary noise within a predetermined frequency band as a function of the distance (d) between the first and second surfaces in a range of distances where the arrangement remains stable;
- determining a maximum obtainable reduction in power RP_{max} of the total amount of noise relative to the primary noise within said range;
- locating said sensors relative to said actuators such that the reduction in power RP of the total amount of noise relative to the primary noise within said predetermined frequency band is within the following range:

$$0.9xRP_{max} \leq RP \leq RP_{max}$$

where both RP and RP_{max} are expressed in decibel.

11. Method according to claim 10 wherein in the arrangement the number of sensors (2(m)) equals the number of actuators (3(n)) and equals the number of controllers (5a(i), 5b(i)), each controller (5a(i), 5b(i)) receiving one of the plurality of sensor signals (p(m)) as input signal and controlling one of the plurality of the actuators (3(n)), the plurality of actuators being arranged in rows and columns, mutual distances between adjacent columns and mutual distances between adjacent rows being equal to a predetermined actuator distance d_x, the plurality of sensors being arranged in the same way as the plurality of actuators, the distance d between the first and the second surfaces being selected to meet the following condition:

$$0.5xd_x \leq d \leq d_x$$

12. Method according to claim 10 wherein in the arrangement the number of sensors does not equal the number of actuators, the plurality of actuators being arranged in rows and columns, mutual distances between adjacent columns and mutual distances between adjacent rows being equal to a predetermined actuator distance d_x, the plurality of sensors being arranged in a regular pattern of rows and columns, each actuator being controlled based on a number of sensor signals, the distance d between the first and the second surfaces being selected to meet the following condition:

$$0.5xd_x \leq d \leq d_x$$

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BO 42162 EUR

EPO - DG 1

03. 11. 1998

Abstract

Noise reduction arrangement including:

- a plurality of actuators (3(n)) for generating secondary noise (**p_s**) to reduce primary noise (**p_p**) and being located in a first surface;
- a plurality of error sensors (2(m)) located in a second surface parallel to the first surface for sensing a total amount of noise resulting from the primary noise after being reduced by the secondary noise;
- a plurality of control means (5(i)) for controlling the actuators (3(n)) based on the sensor outputs,

wherein the distance (d) between the first and second surfaces is such that reduction in power RP of the total amount of noise relative to the primary noise within a predetermined frequency band is within the following range:

$$0.9 \mathrm{x} RP_{max} \leq RP \leq RP_{max}$$

in which RP_{max} is the maximum obtainable reduction in power of the total amount of noise relative to the primary noise, both RP and RP_{max} being expressed in decibel.

[figure 1b]

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Fig 1a

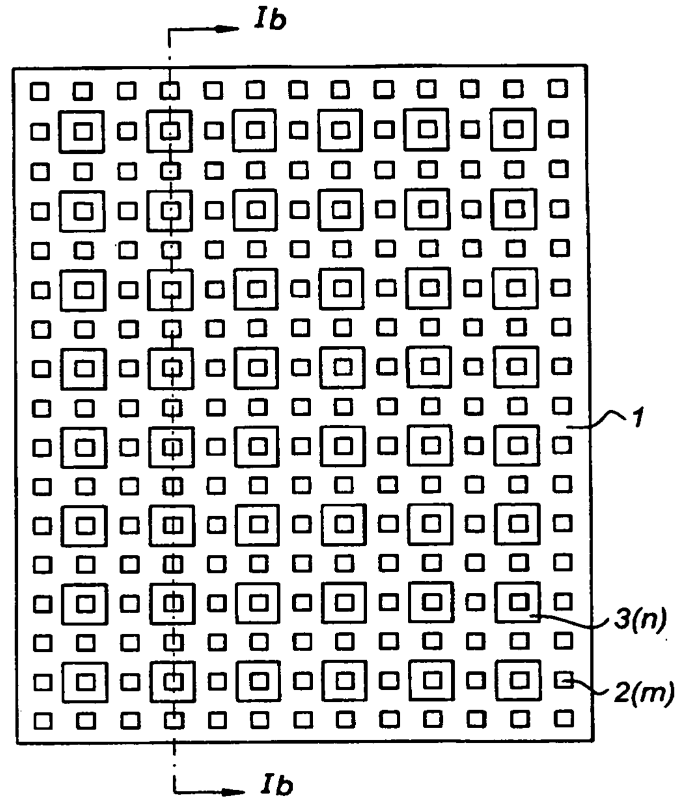
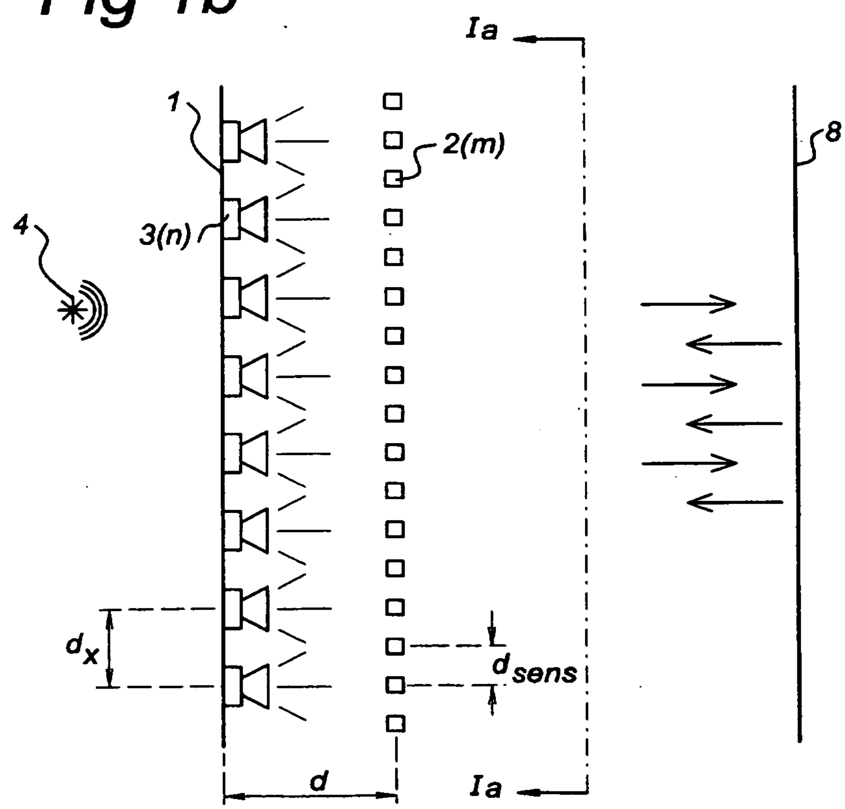


Fig 1b



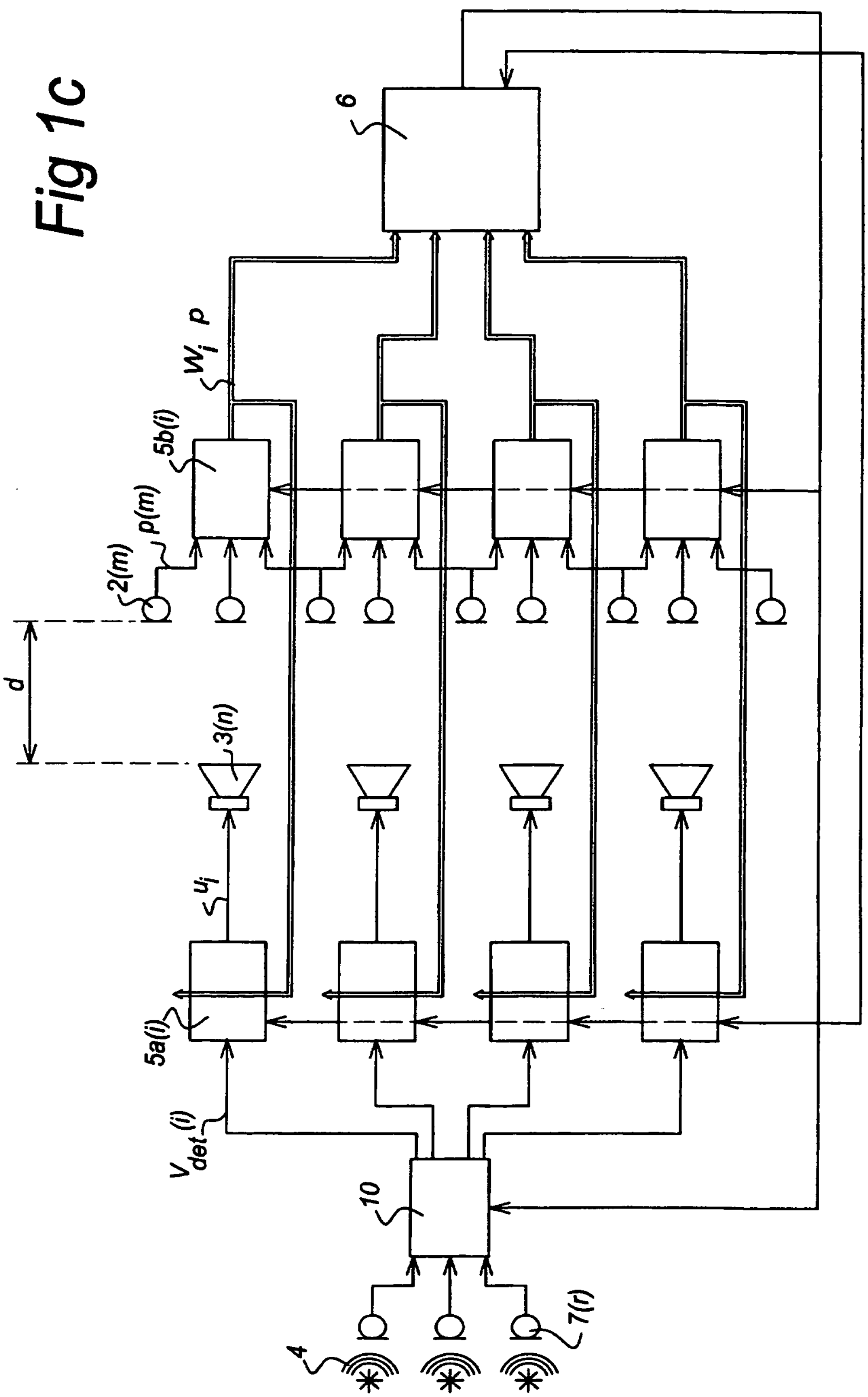


Fig 1c

Fig 2

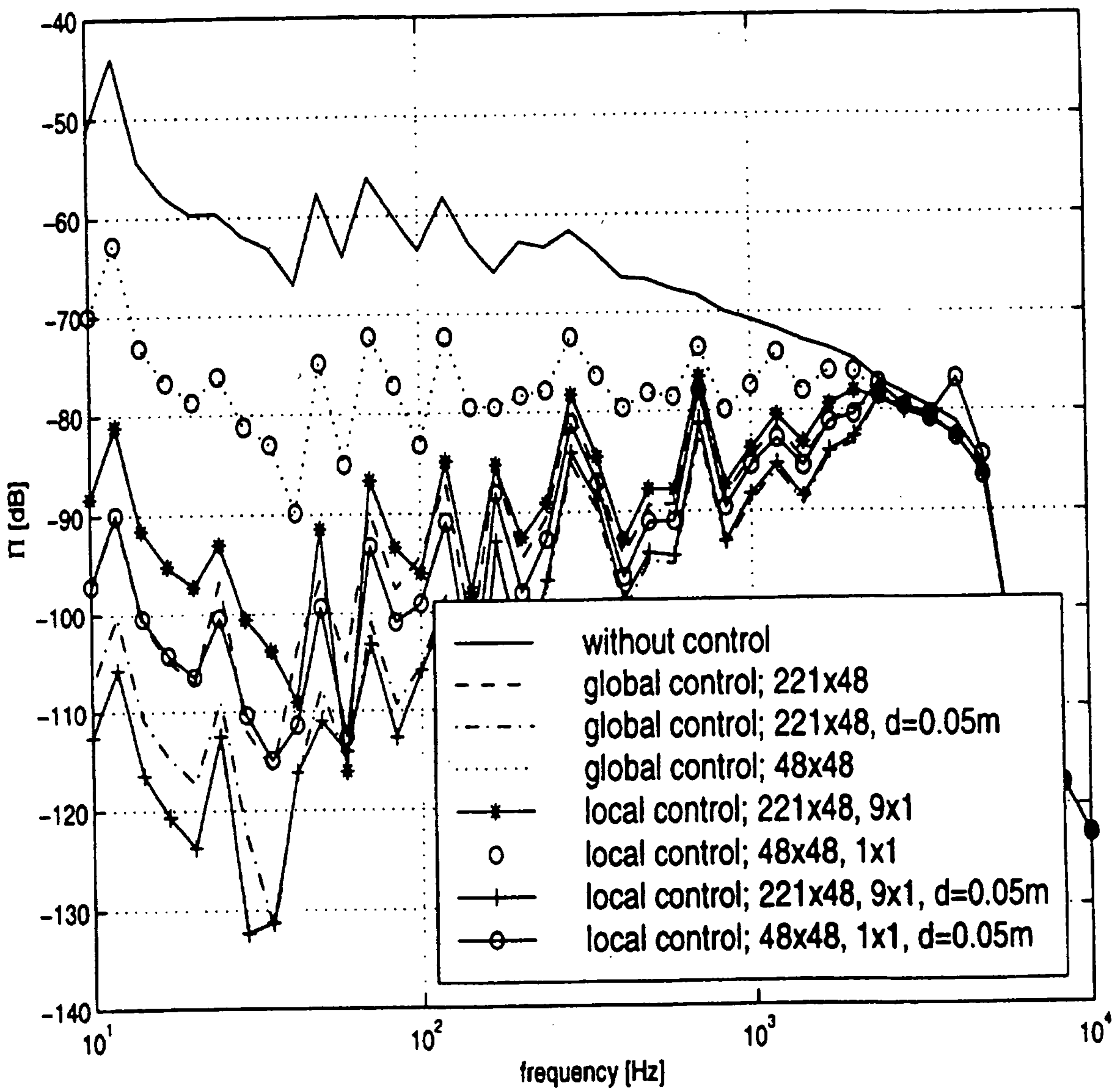
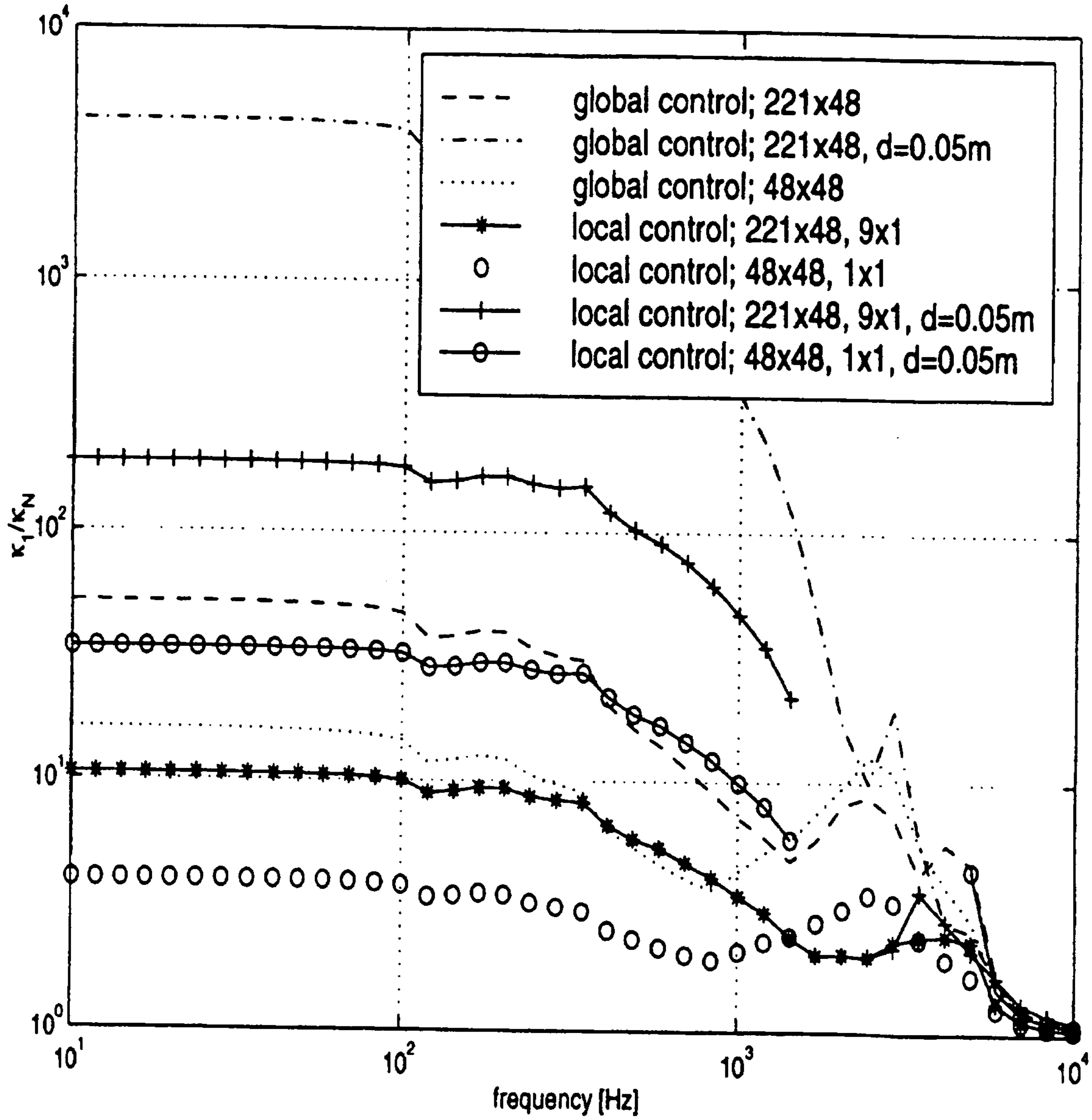

-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
Π [dB]
10^1
10^2
10^3
10^4
frequency [Hz]
without control
global control; 221x48
global control; 221x48, d=0.05m
global control; 48x48
local control; 221x48, 9x1
local control; 48x48, 1x1
local control; 221x48, 9x1, d=0.05m
local control; 48x48, 1x1, d=0.05m

Fig 3



10^4
10^3
10^2
10^1
10^0
κ1/κN
10^1
10^2
10^3
10^4
frequency [Hz]
global control; 221x48
global control; 221x48, d=0.05m
global control; 48x48
local control; 221x48, 9x1
local control; 48x48, 1x1
local control; 221x48, 9x1, d=0.05m
local control; 48x48, 1x1, d=0.05m

Fig 4

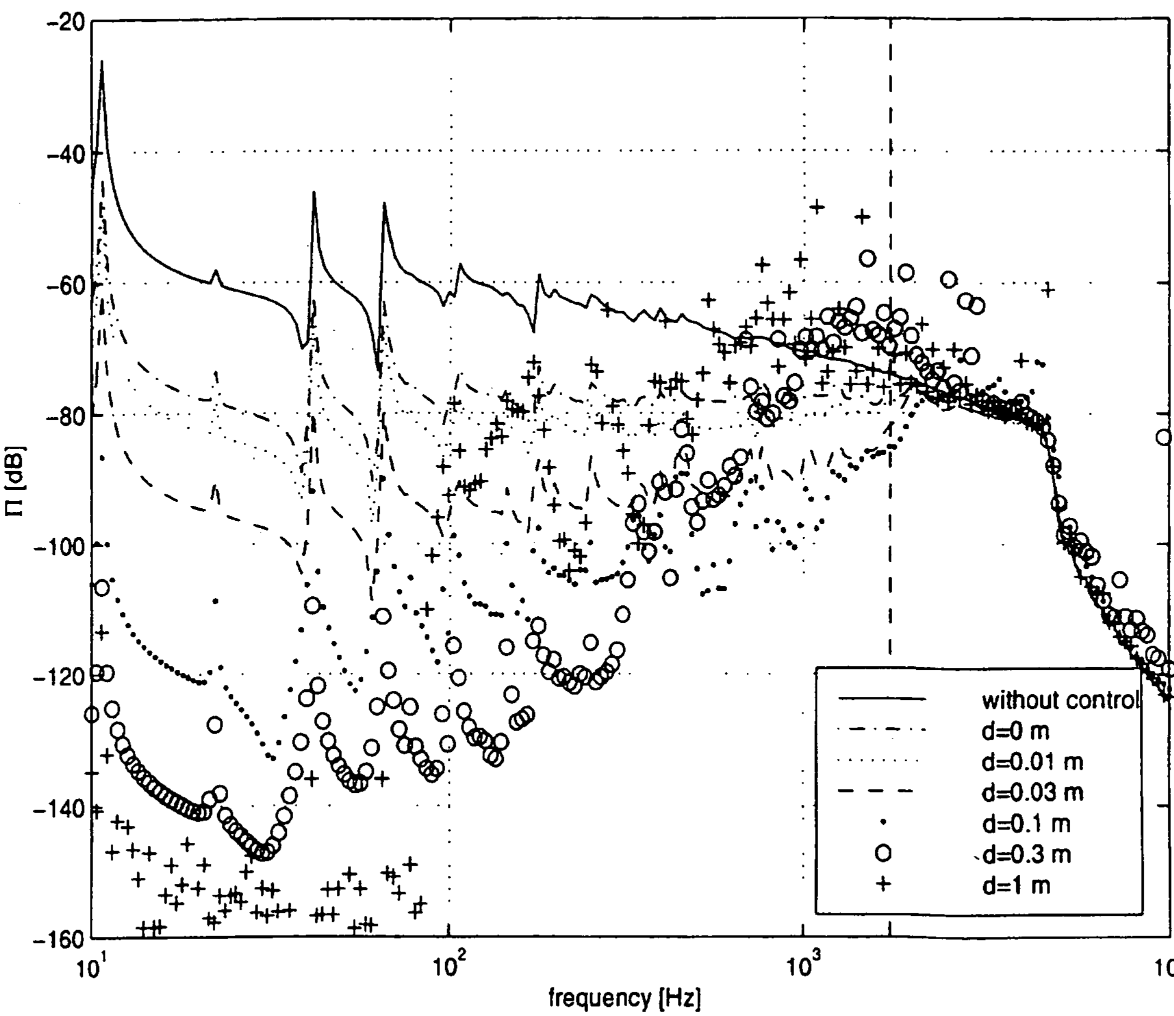
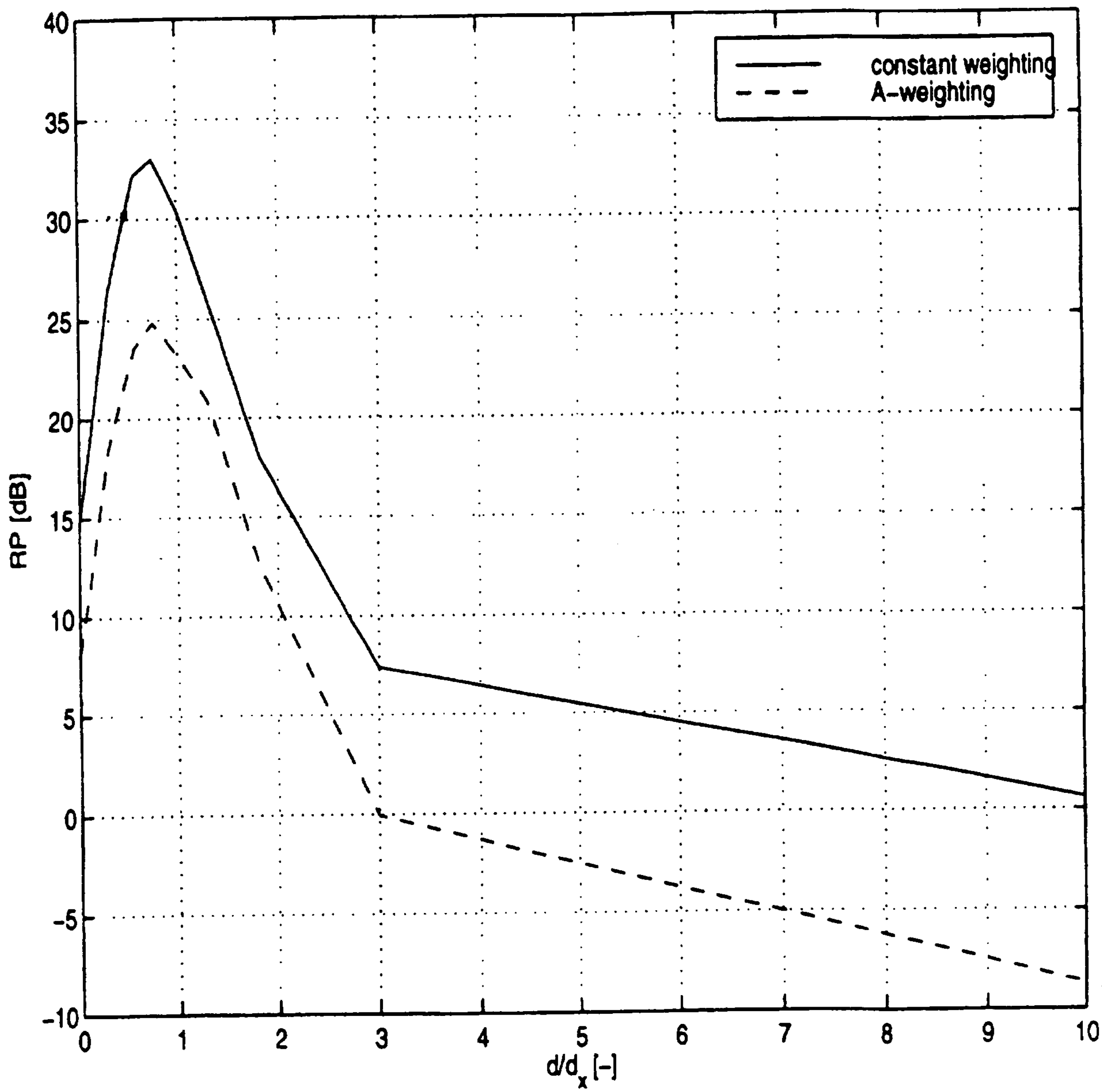

-20
-40
-60
-80
-100
-120
-140
-160
Π [dB]
10^1
10^2
10^3
10^4
frequency [Hz]
without control
d=0 m
d=0.01 m
d=0.03 m
d=0.1 m
d=0.3 m
d=1 m

Fig 5



constant weighting
A-weighting
RP [dB]
d/d_x [-]
40
35
30
25
20
15
10
5
0
-5
-10
0
1
2
3
4
5
6
7
8
9
10

Fig 6

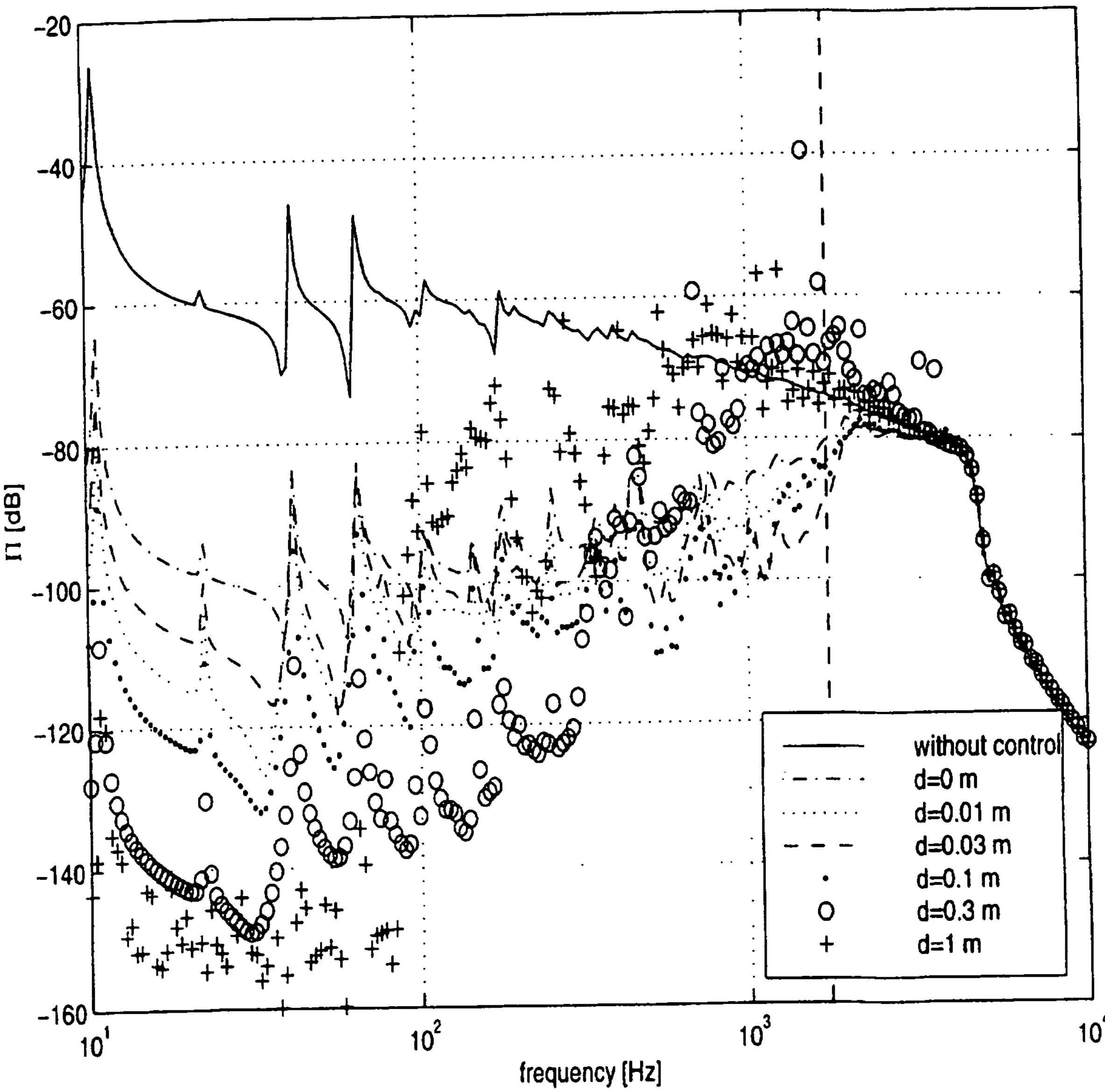
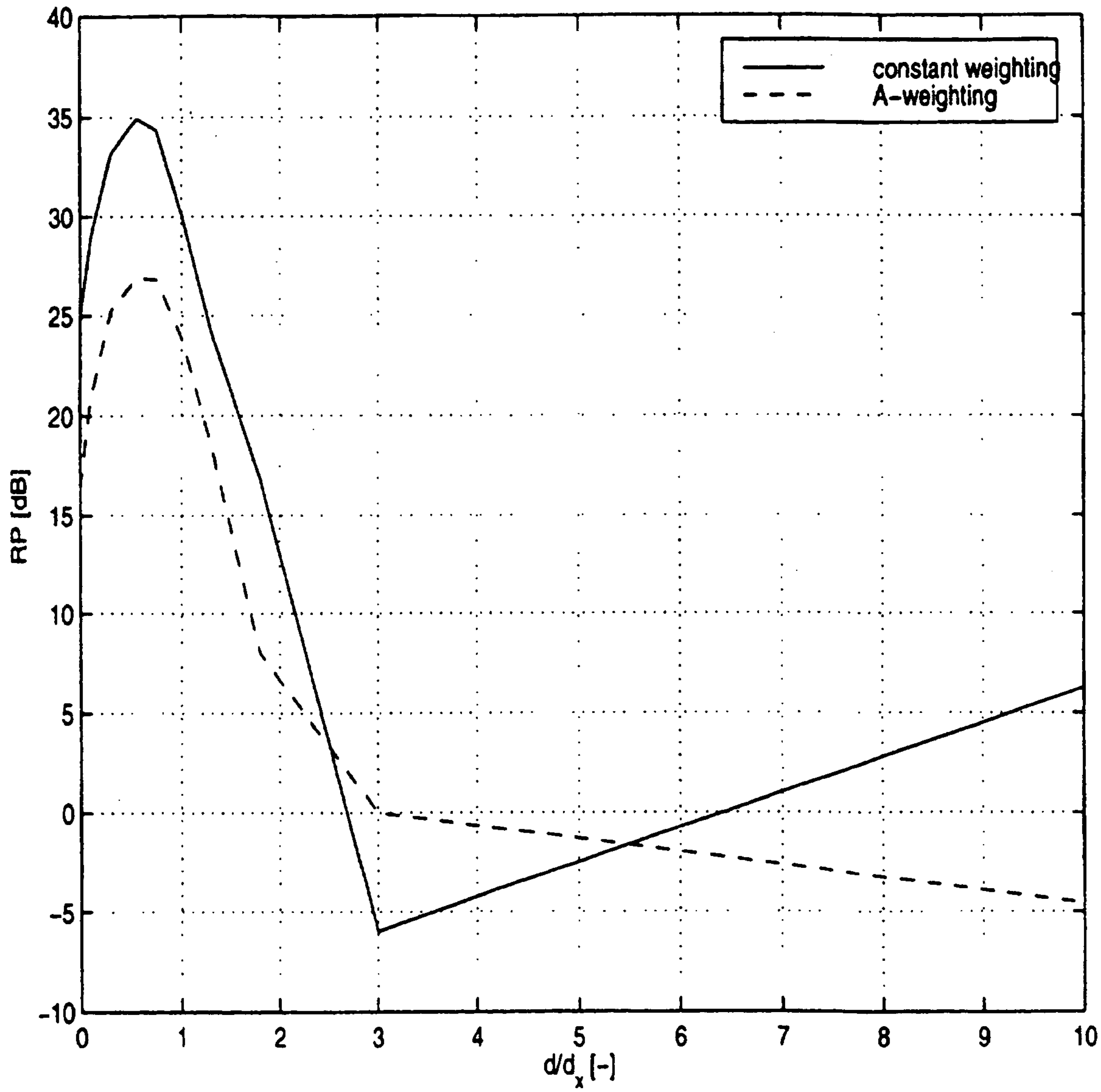

-20
-40
-60
-80
-100
-120
-140
-160
Π [dB]
10^1
10^2
10^3
10^4
frequency [Hz]
without control
d=0 m
d=0.01 m
d=0.03 m
d=0.1 m
d=0.3 m
d=1 m

Fig 7



constant weighting
A-weighting
RP [dB]
d/d$_x$ [-]
40
35
30
25
20
15
10
5
0
-5
-10
0
1
2
3
4
5
6
7
8
9
10

Fig 8

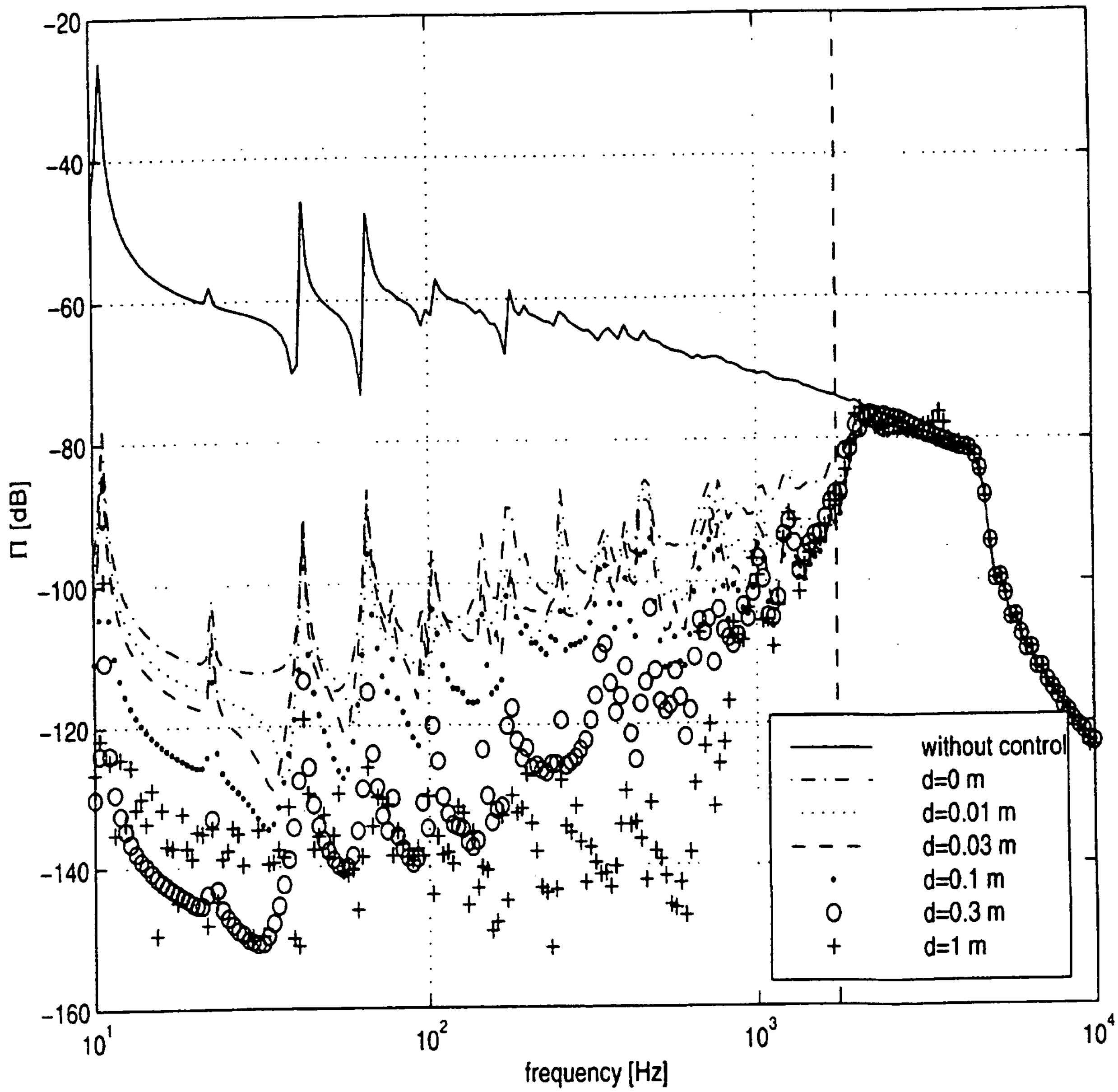
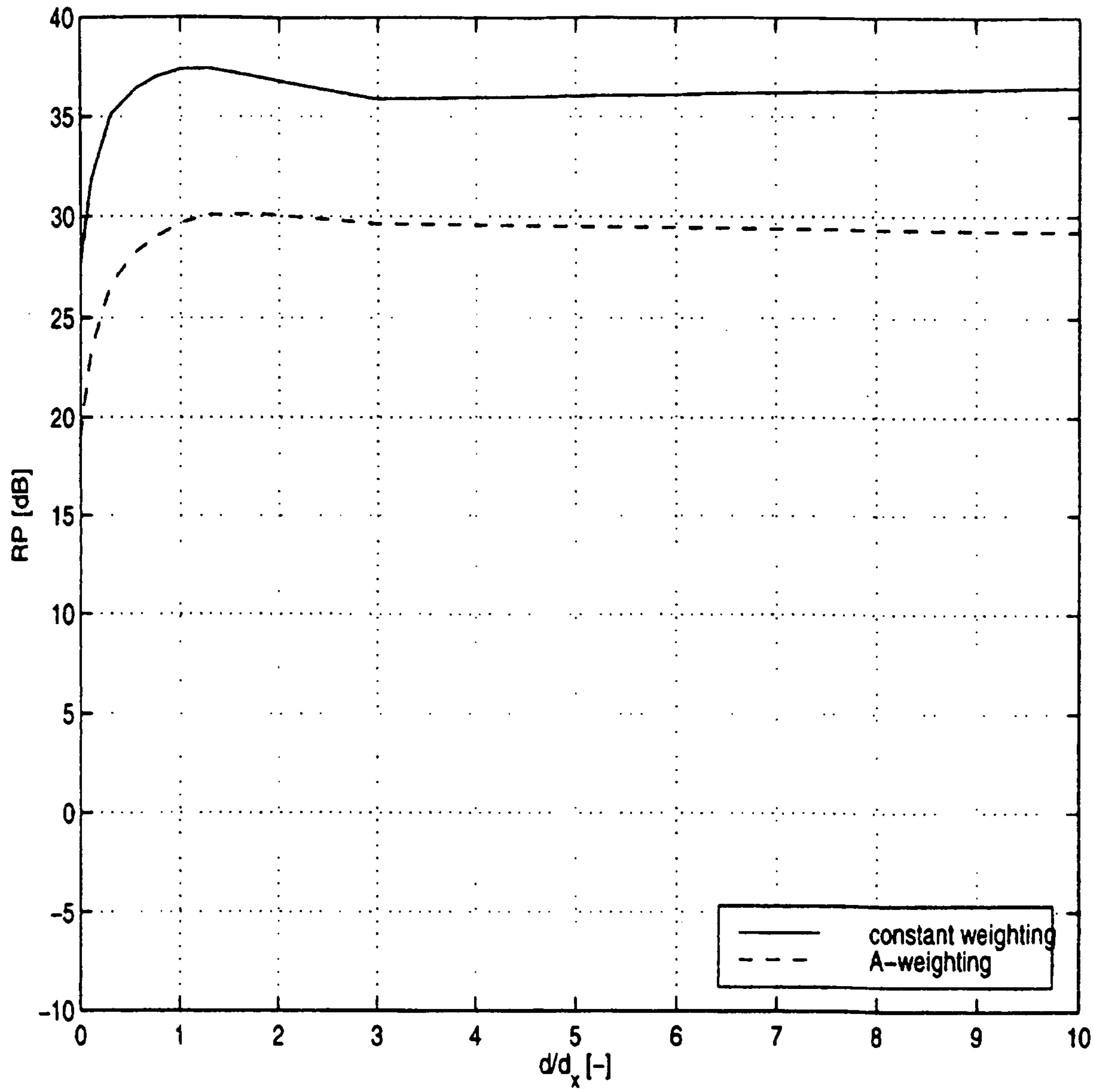
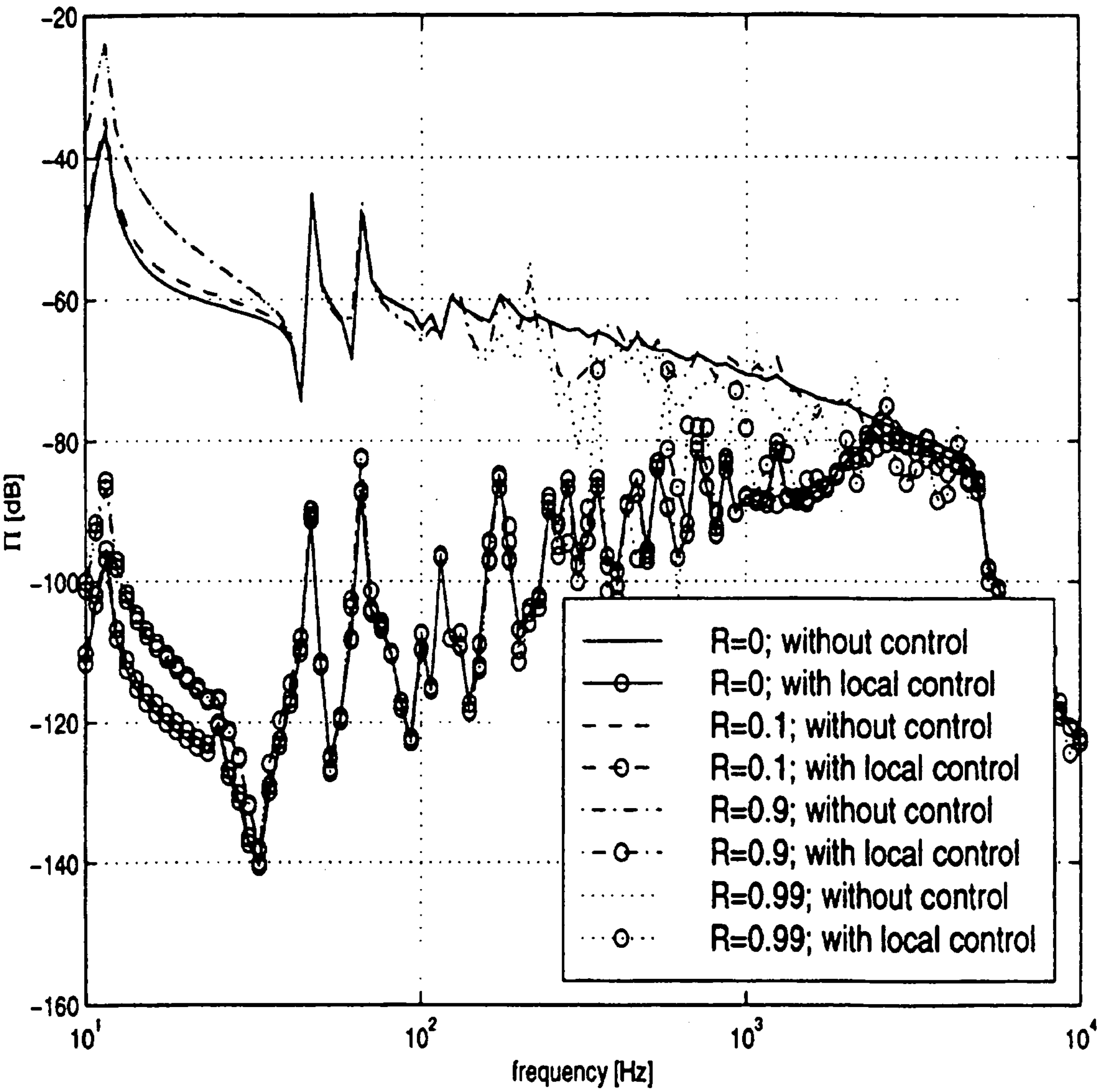

-20
-40
-60
-80
-100
-120
-140
-160
Π [dB]
10^1
10^2
10^3
10^4
frequency [Hz]
without control
d=0 m
d=0.01 m
d=0.03 m
d=0.1 m
d=0.3 m
d=1 m

Fig 9



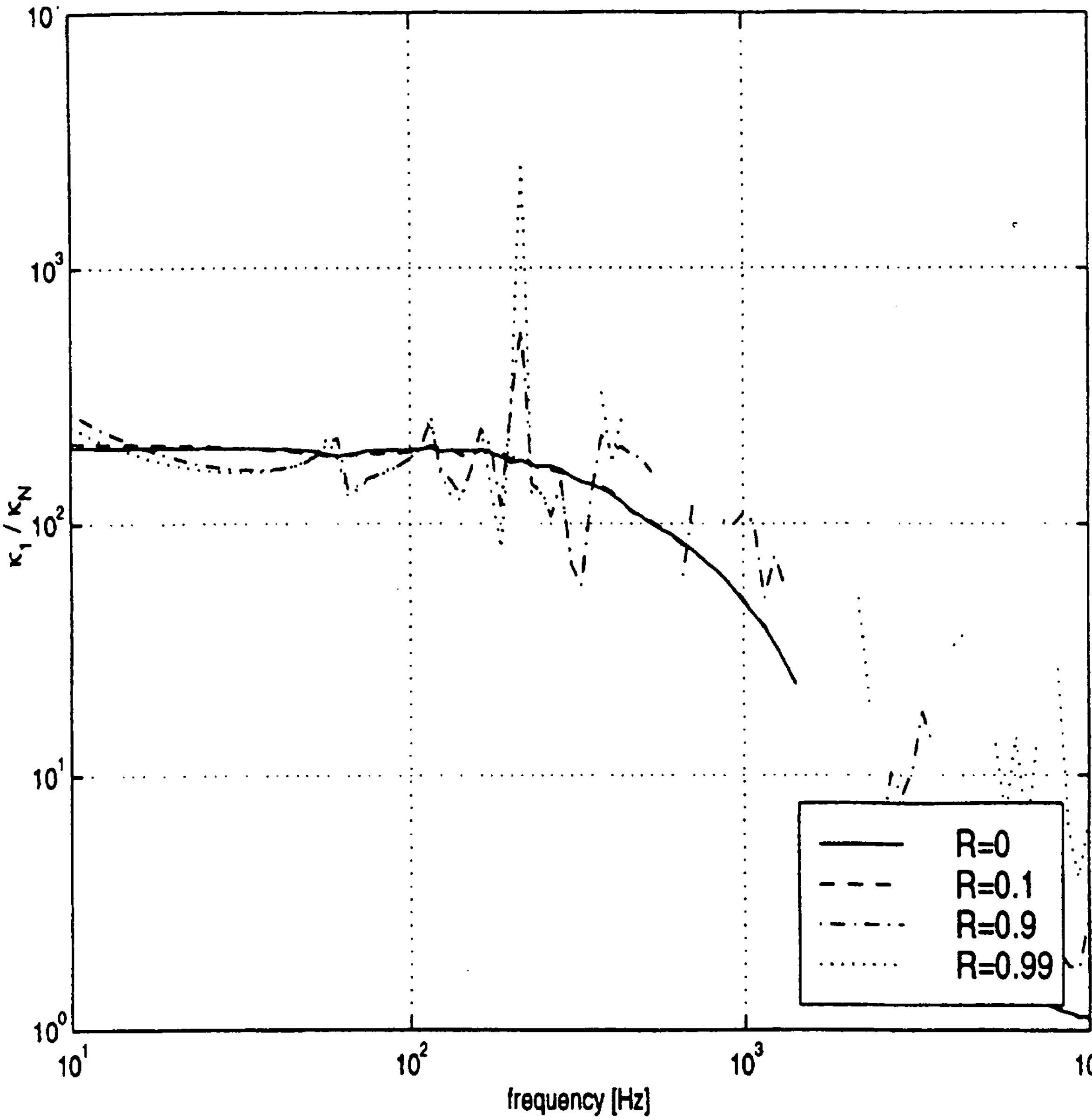
40
35
30
25
20
15
10
5
0
-5
-10
RP [dB]
0
1
2
3
4
5
6
7
8
9
10
d/d_x [-]
constant weighting
A-weighting

Fig 10



-20
-40
-60
-80
-100
-120
-140
-160
Π [dB]
10^1
10^2
10^3
10^4
frequency [Hz]
R=0; without control
R=0; with local control
R=0.1; without control
R=0.1; with local control
R=0.9; without control
R=0.9; with local control
R=0.99; without control
R=0.99; with local control

Fig 11


10^4
10^3
10^2
10^1
10^0
κ_1 / κ_N
10^1
10^2
10^3
10^4
frequency [Hz]
R=0
R=0.1
R=0.9
R=0.99